Assessment of a bolted-flange connection for ITER Test Blanket Module

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Problem position

The Test Blanket Module (TBM) are core components of ITER.

Several designs of tritium Breeding Blankets are proposed. All these concepts share a common feature: they have to be connected to a network of pipes, referred to as `Pipe Forest (PF)'. The PF connects the AEU to the TBM and will provide fluids for tritium process and coolant (gas/water).

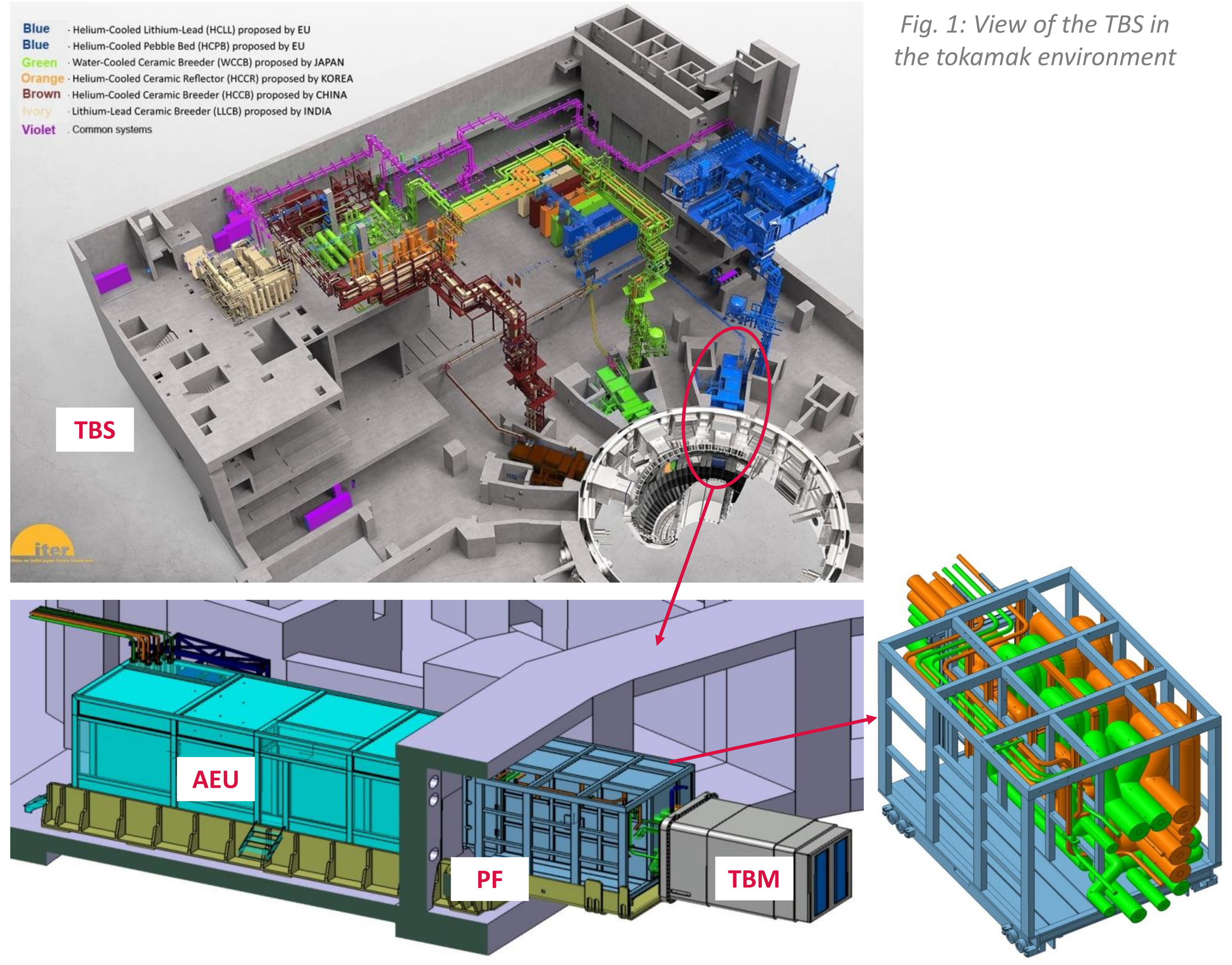


Fig. 1: View of the TBS in the tokamak environment

The PF design is strongly constrained. In addition to stringent definition requirements, the PF has to be conceived under ALARA principles. In maintenance phase, the hands-on operational time required for connection/disconnection of the PF shall be minimized and Remote Handling (RH) operation will be considered when possible.

Two technical solutions are considered at the TBM/PF interface: welded and bolted flange connection. The present study focuses on the latter.

Mechanical design & Numerical model

Among the different concepts, we focus on three fluid lines: lithium-lead, water and helium.
Leak-rate criterion defined regarding ITER safety requirements and conditions:

- Liquids: `bubble tight' crit. with HELICOFLEX® seal
- Gas: `helium tight' crit. with double torus HELICOFLEX® seal for leak monitoring

Tab. 1: Design conditions

	Lithium-Lead	Water	Helium
Pipe size	DN25	DN65	DN80
Pipe material	Eurofer	SS-316L	SS-316L
Outer diam. [mm]	33.7	76.1	88.9
Thickness [mm]	5	12.5	8.8
Flange `Class'	300	2,500	2,500
Bolts	4 × M16	8 × M30	18 × M24
Bolt tension [kN]	20	30	60
Temperature [°C]	340	345	525
Pressure [MPa]	0.9	18.8	9.8
Traction [N]	1,000	3,025	1,930
Bending [N·m]	325	2,975	7,175
Torsion [N·m]	100	850	2,685
Leak rate criterion	`bubble tight'	`bubble tight'	`helium tight'

Temperature below 400 °C: industrial flange NF-EN 1759
Above 400 °C: creep effects → custom, water cooled flanges

Flanges are rotatable and thermally insulated.

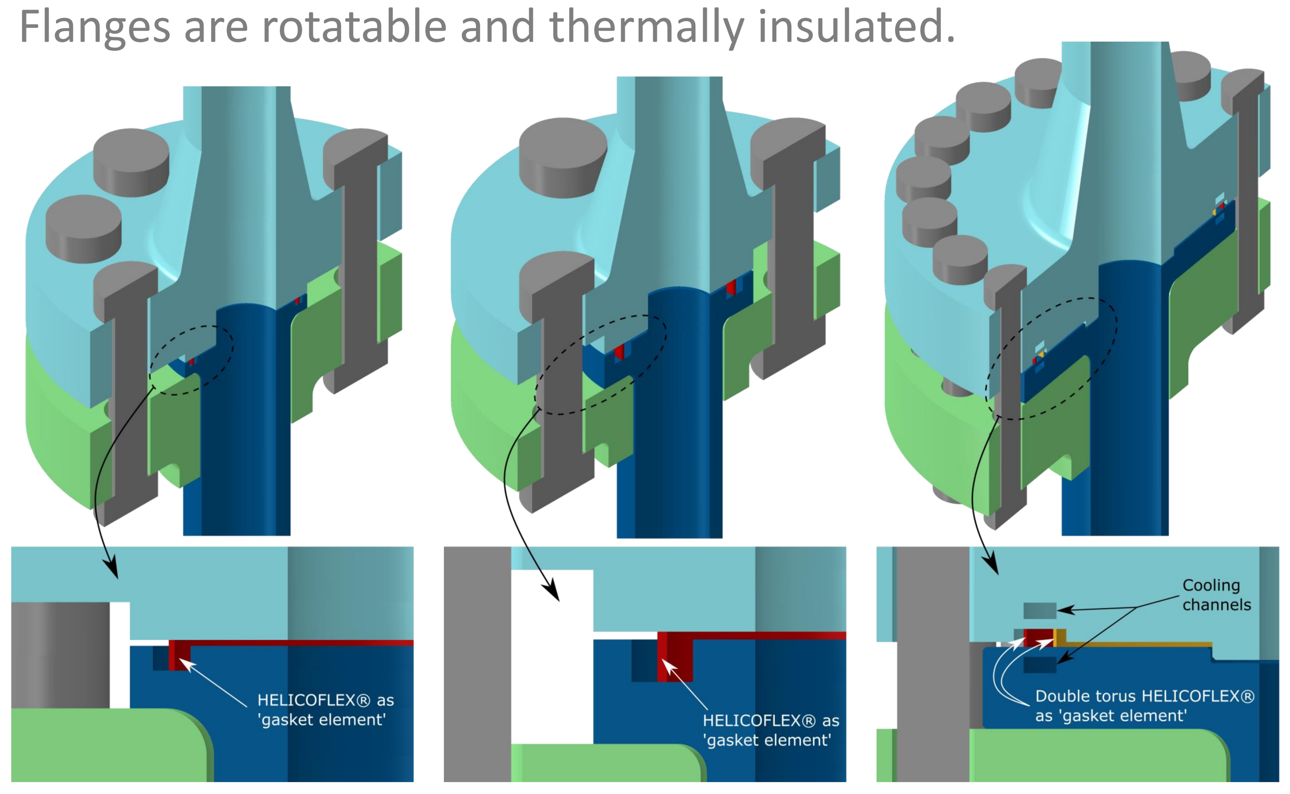


Fig. 2: Simplified half view of the flanges

For water and lithium-lead assembly:

- Static, linear elastic analysis, constant temperature
- Mat. prop. from RCC-MRx and ASME-BPVC
- Seals behaviours obtained from fine-scale FEM simulations

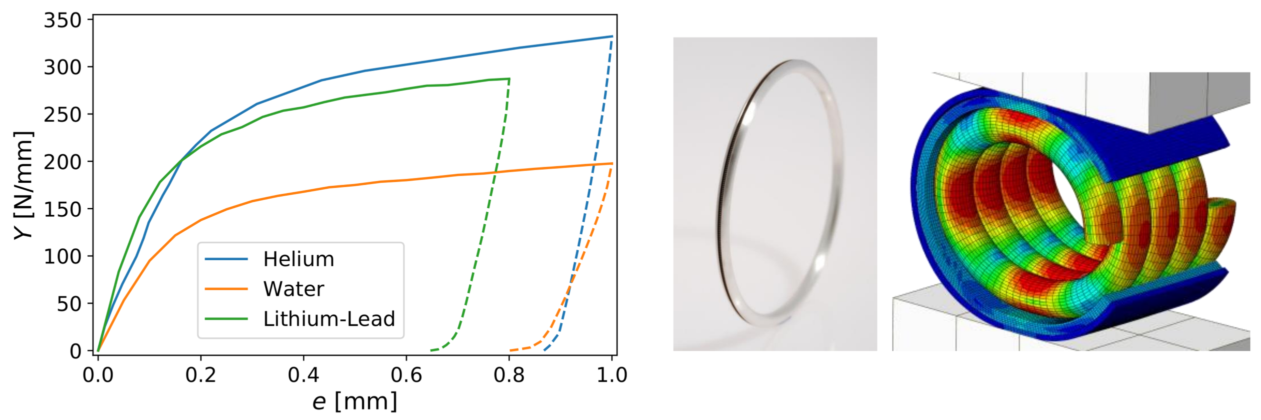


Fig. 3: Load-compression curve of the different seals

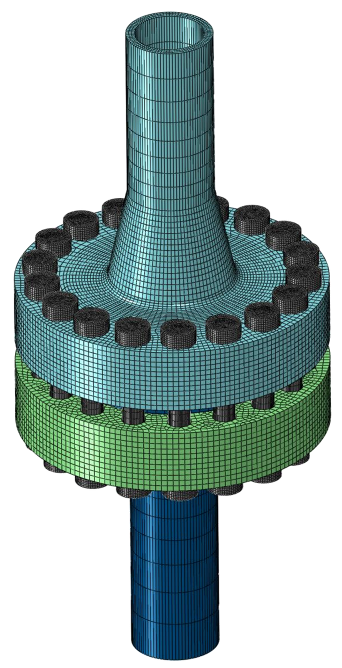


Fig. 4: Mesh of the helium pipe

Boundary conditions and loadings:

1. One face of pipe blocked (except radial disp.), bolt loads
2. Ext. mechanical loads (traction, bending, torsion)
3. Pipe and channels pressure, temperature and convection

For helium assembly:

- Static, linear elastic, fully coupled thermomech. analysis

Thermal contact conductance:

- global steel-steel: values from lit.
- silver seal-steel: 15×10³ W/m²·K (exp. data)

Convection coefficient:

$$h_c = \mathrm{Nu}\,\frac{\lambda_f}{D_h}, \qquad \mathrm{Nu} = 0.023\,\mathrm{Re}^{0.8}\mathrm{Pr}^{0.333}$$

- gaseous helium pipe, assuming Q = 1.4 kg/s at 525 °C
  $h_c^0 = 1{,}115\ \mathrm{W/m^2 \cdot K}$
- water cooling channels, assuming v = 2 m/s at 34 °C and 1 MPa
  $h_c^1 = 9{,}280\ \mathrm{W/m^2 \cdot K}$

Simulations using ABAQUS®

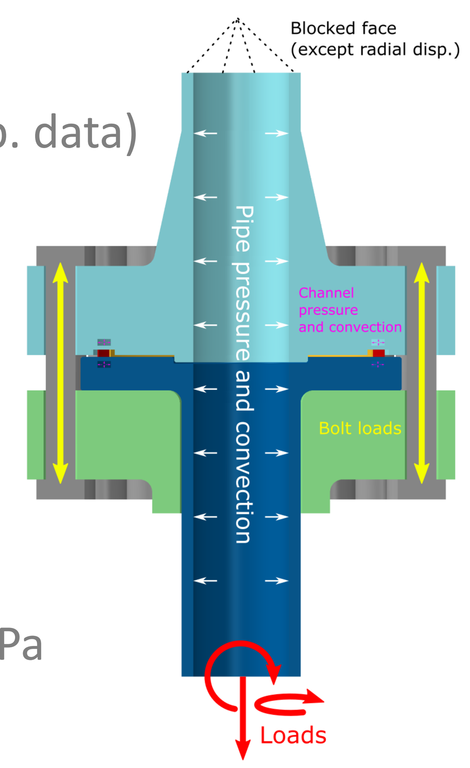


Fig. 5: Application of the BC and loadings

Results

Water & Lithium-Lead flanges

Maximum equivalent stress at the socket, close to the groove

- SS-316L: $R_{p0.2} = 101$ MPa at 340 °C
- Eurofer: $R_{p0.2} = 423$ MPa at 340 °C
- B21 Class 1: $R_{p0.2} = 880$ MPa at 340 °C

Important (elastic) stresses

- accommodated with a small amount of plastic strain

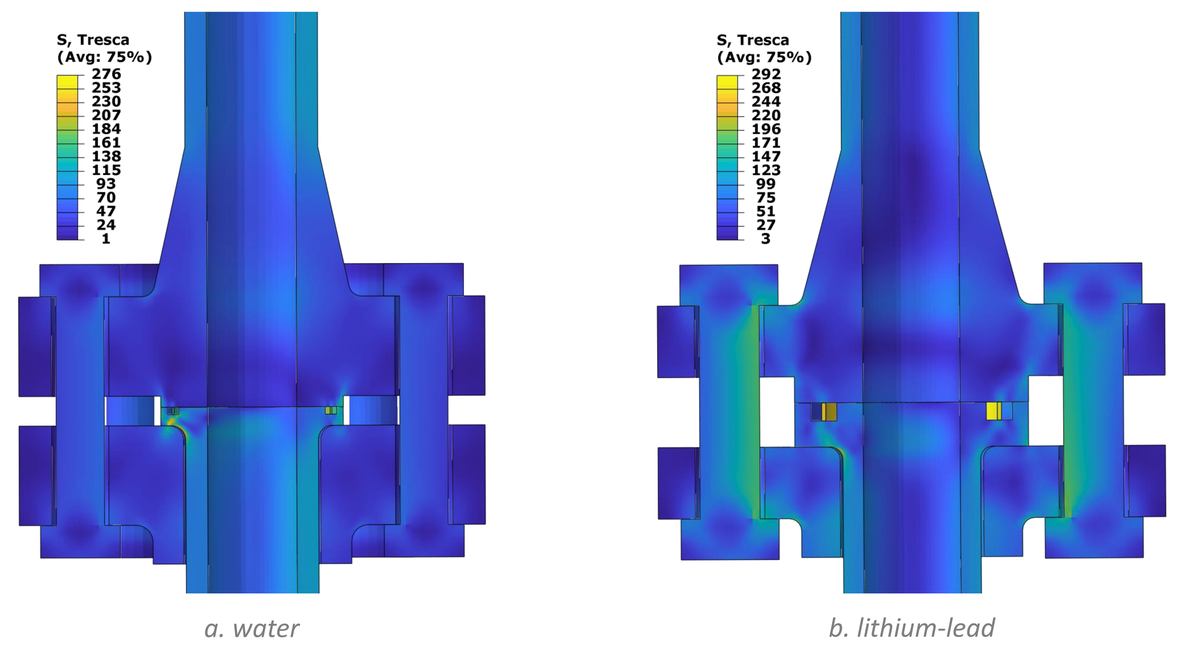


Fig. 6: Tresca equivalent stress (in MPa) in the flanges

Tab. 2: Results at particular locations in the assemblies

	Lithium-Lead	Water	Helium (2 cool. ch.)	Helium (1 cool. ch.)
σ_{max} [MPa]	250	276	1,340	1,097
σ_{bolt} [MPa]	212	81	383	521
σ_{pipe} [MPa]	107	109	202	203
T_{max} [°C]	340	345	525	525
T_{bolt} [°C]	—	—	221	361
T_{seal} [°C]	—	—	64	417
$T_{channel}$ [°C]			62	417

Helium flange

Important stresses induced by the large thermal gradient.

- maximal around the socket
- less important if one cooling is inactivated
- plastic permanent marking

Reasonable stress in the fasteners with two cooling channels

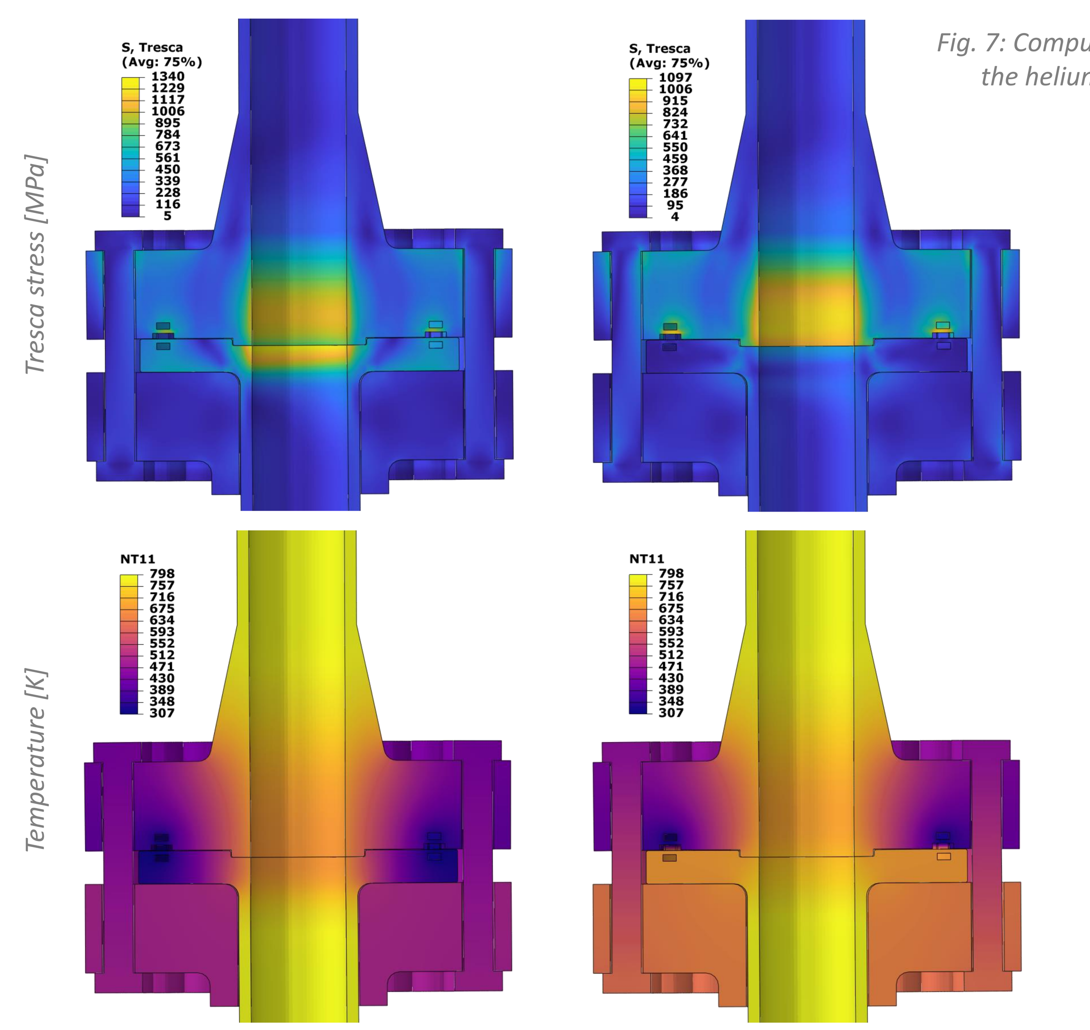


Fig. 7: Computed fields in the helium flange

Temperature remains low in the bolts and the seals with two cooling channels, allowing potential thermal design margins.

Temperature reaches unreasonable levels if a single cooling channel is used.

- Two cooling channels are necessary

Cooling heat flux of 3.5 kW, a rather high value but within the design acceptance margins.

Monitoring of the effect of water velocity (through h_c^1) on the cooling power:

- still important even for low h_c^1 due to high convection on the gaseous helium side
- can be explained by the simple following model

$$\frac{\varphi}{\varphi_\infty} = \frac{\mathrm{Bi}}{1+\mathrm{Bi}}$$

$$\frac{1}{\mathrm{Bi}} = \frac{R_1 - R_0}{\ln R_1 - \ln R_0}\left(\frac{1}{R_0 \mathrm{Bi}_0} + \frac{1}{R_1 \mathrm{Bi}_1}\right)$$

$$\mathrm{Bi}_j = h_c^j\,(R_1 - R_0)/\lambda_s\,, \qquad j = 0{,}1$$

Harmonic dependence of φ on Bi_1 → difficult to decrease φ
Geometrical optimisation of the channels remains a possibility to reduce the cooling power.

h_c^0 [W·m⁻²·K⁻¹]	h_c^1 [W·m⁻²·K⁻¹]	φ [kW]
1,115	9,280	3.53 ○
1,115	3,061	3.37 ○
1,115	845	2.91 ○
1,115	382	2.39 ○
6,115	9,280	4.31 □
3,115	9,280	4.09 □
350	382	1.90 □

Tab. 3: Cooling heat fluxes

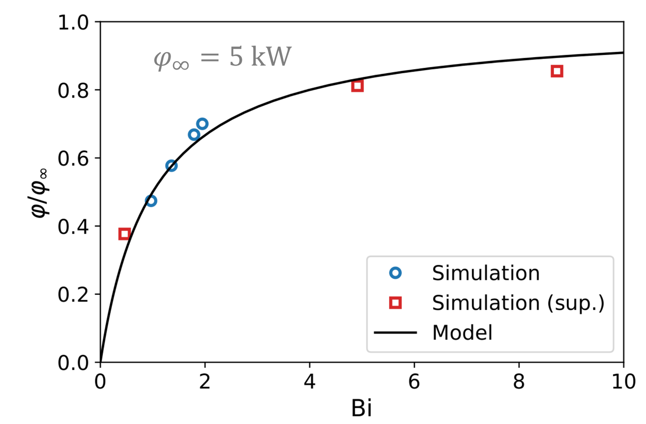
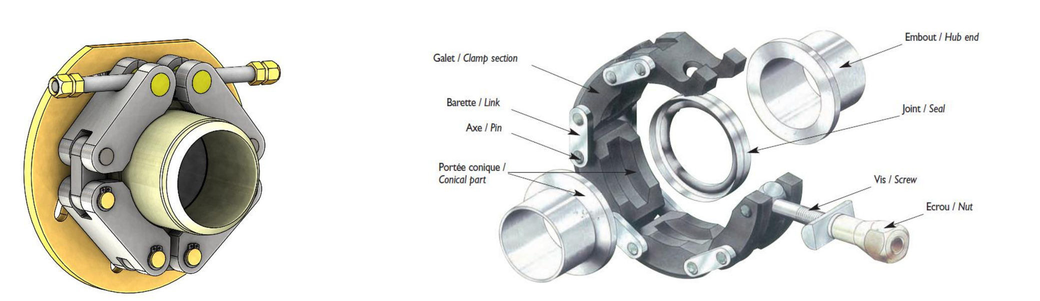


Fig. 8: Dimensionless cooling heat flux

Conclusions

- Implementation of industrial standards for water and lithium-lead bolted flanges.
- Custom design for helium pipe with water cooled flanges.
- FEM thermomechanical analysis demonstrate the feasibility of flange connections.

To comply with ALARA approach, the studies continue considering design of flange mounted with Quick Disconnecting System (QDS) to replace the fasteners.



Acknowledgements

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